about the time of transit, the aspect of the head and nucleus of the comet was rapidly changing from day to day. Before the transit the part of the head facing the sun was principally visible; near the transit another part of the comet's head was visible from the earth; while after transit the hotter side of the coma would again gradually come into view. It is quite conceivable that this presentation of such different portions of the comet might exhibit notable differences of spectrum.

From a series of preliminary experiments it has been found that very remarkable changes of intensity of these carbon bands may be brought about by simple variations of the conditions of volatilisation; so much so, that this would probably serve as the more satisfactory reason for differences between various photographs of the comet's spectrum, provided, of course, that any known instrumental or atmospheric differences are duly considered.

I am indebted to Mr. J. P. H. Wilkie, photographer to the Observatory, for help in the preparation of the illustrations to this report.

The Distribution of Electric Force in the Crookes Dark Space.

By F. W. Aston, B.Sc., A.I.C., Trinity College, Cambridge.

(Communicated by Sir J. J. Thomson, F.R.S.—Received November 22, 1910,—Read January 12, 1911.)

Introductory.

The electric force in the Crookes dark space and the negative glow has been the subject of a considerable number of investigations. The first determination was made by Schuster,* whose results indicate the presence of a positive charge of electricity, whose density decreases in geometrical progression as the distance from the cathode increases in arithmetical progression. Graham† found a curious drop in potential near the cathode, but Wehnalt‡, repeating these experiments, was unable to find this drop of potential, and ascribes it to the fact that the exploring points were not in the direct line of the current. Skinner§ came to the conclusion that all the fall of potential occurs at the surface of the cathode. Recently, Westphal|| has made a careful series of observations with cathodes of different metals

* 'Roy. Soc. Proc.,' 1890, vol. 47, p. 526.
† 'Wied. Ann.,' 1898, vol. 64, p. 49.
‡ 'Ann. d. Phys.,' 1903, (4), vol. 10, p. 542.
§ 'Phil. Mag,' 1902, 6, vol. 2, p. 616.
|| 'Verhand. d. Deutsch. Phys. Ges.,' 1910, vol. 12.

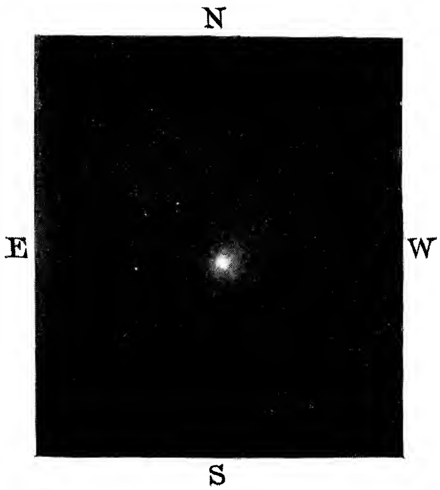


FIG. 1.

1910, May, 23 d. 9 h. 20 m. to 9 h. 50 m.

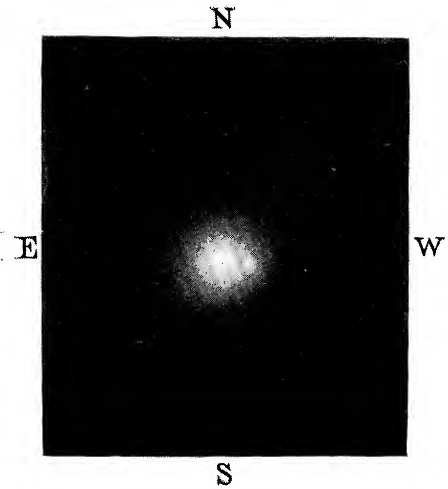


FIG. 2.

1910, May, 26 d. 9 h. 40 m. to 10 h. 10 m.

(Photographs of the Nucleus of Halley's Comet.)

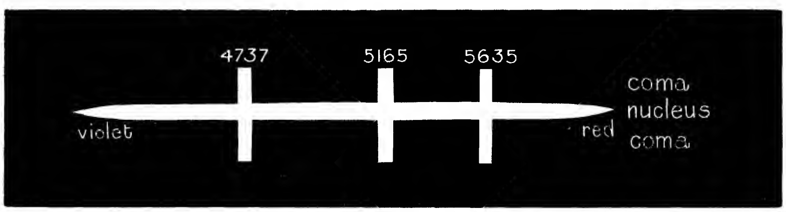


FIG. 3.—Visual Observations of Spectrum, May 22, 23, 26.

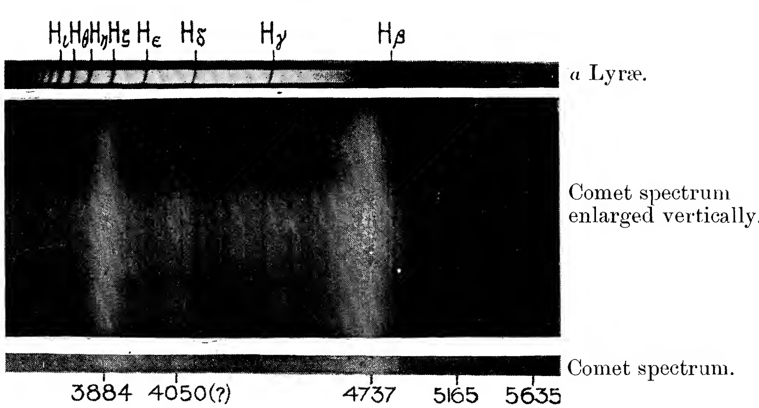


FIG. 4.—Photograph of Comet Spectrum, with α Lyræ comparison.
(Quartz-calcite Spectrograph, 2-inch aperture, 18-inch focus.)

in several gases, using a single exploring point, in which he finds a definite fall of potential—*e.g.* about 80 volts for Al in H_2—at the surface of the cathode, the electric force a few millimetres away appearing from his curves nearly uniform.

Now all these measurements were made by introducing exploring sounds, *i.e.* metallic wires or points, into the discharge, the observers trusting to these taking up the potential of the gas by which they were surrounded. The danger of such assumption has been pointed out by Sir J. J. Thomson,* and for measurements made inside the dark space it seems entirely unwarranted.

Fortunately, however, there is an alternative method, which involves no doubtful assumptions, and does not introduce substantial obstacles into the discharge. Its simplicity and elegance cannot fail to appeal to anyone investigating this field of research. This method was suggested by Sir J. J. Thomson, and used by him recently in determining the potential distribution in the striated discharge;† it consists in shooting a beam of cathode rays transversely through the discharge, the deflection of these being taken as a measure of the electric force at that point.

It appeared to the author that this method might be used with advantage to determine the distribution of potential near the cathode under the conditions used by him in obtaining measurements of the length of the dark space,‡ these conditions being briefly:—

Electrodes in the form of circular discs filling the discharge tube, the latter being very much wider than the maximum length of the dark space, so that the edge effect will be comparatively small.

Current density always greater than that necessary to cover the cathode with glow, and to cause the positive column to disappear.

It was to be expected, from the numbers obtained in the above research, that the electric forces to be measured would rise as high as 300 volts per centimetre. Now it can be easily shown that, for an electron to attain sufficient velocity to cross a tube 10 cm. wide under such a force with a small enough deflection, it is necessary for it to fall through a potential of about 20,000 volts. The principal problem to solve, therefore, was the design of a secondary discharge tube, which, while working at a pressure necessary to give a dark space of 2 to 3 cm. in the main tube, would deliver a homogeneous beam of cathode rays under a working potential corresponding to a centimetre spark in air.

* "Conduction of Electricity through Gases," 2nd ed., p. 531.

† 'Phil. Mag.,' Oct., 1909, vol. 18, pp. 441—451.

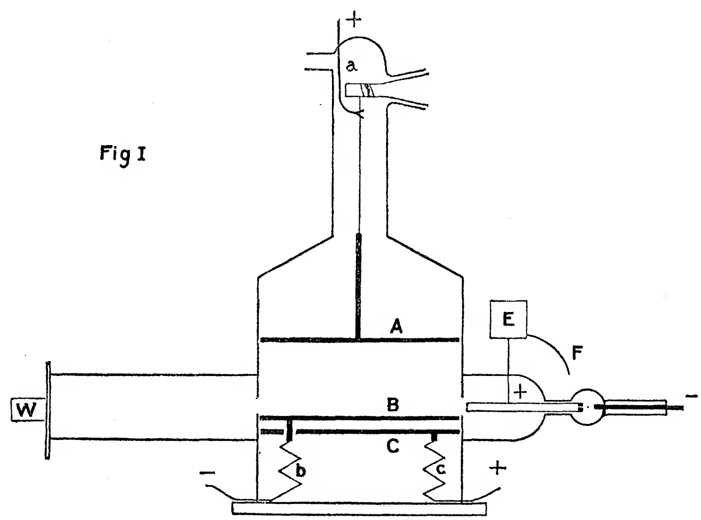
‡ F. W. Aston, 'Roy. Soc. Proc.,' 1907, A, vol. 79.

It was only after a tedious and dispiriting investigation, in which a large number of forms of secondary tube were tried—the whole apparatus having to be completely re-evacuated after each variation—that the necessary conditions were arrived at, when the rest of the research became comparatively easy.

Apparatus.

The arrangement of the apparatus is indicated in fig. 1. The main discharge tube is a large cylindrical bottle 12 cm. wide, with windows cut in the sides, through which the exploring ray is to pass. A, B, and C are three aluminium discs, just filling the tube, and kept at fixed distances

Fig I



apart by a framework of thin glass rods (not shown in the figure). A and B are 6·5 cm. apart, and form respectively the anode and cathode of the main discharge, which is maintained by a large battery of storage cells and controlled by a water resistance. B and C form a system of parallel plates 0·485 cm. apart, to which a known potential could be applied through the flexible leads *b* and *c*, to determine the deflection of the rays in a known uniform field.

As it is almost impossible to maintain a steady current with aluminium electrodes in the presence of mercury vapour, the old method of moving the electrodes up and down with a float supported on mercury was abandoned in favour of the device indicated in the figure. Into the neck of the bottle is fitted a vertical tube, to the side of which is attached a ground-glass joint (a good stop-cock does very well). The plug of this is elongated as a rod, over which is wound a flexible conducting cable made of a few strands of the

finest brass wire, and at the end of this is hung the apparatus to be moved, in this case the three discs. The method of fixing the point of support of the system, and also of supplying the anode lead, will be easily seen from the figure, the cable running under a slight tension through the copper wire fork *a*.

This simple arrangement proved quite faultless in practice, the plates being set at any required point with the greatest ease and accuracy.

At the one window of the main discharge tube was fixed a glass tube 28·5 cm. long, carrying a screen of powdered willemite *w*, at the other the secondary discharge tube. This in its final form is practically an X-ray bulb on a minute scale. The bulb is 1 cm. in diameter, the cathode is a piece of aluminium wire 1·5 mm. thick, the end is ground off perfectly flat and just emerges from the thick-walled tube into the bulb. The anode is a brass tube 10 cm. long, 5 mm. wide, plugged at both ends. The plug at the end nearest the cathode is of brass drilled with a 2 mm. hole, that at the other is of lead sheet pierced at the centre with the finest possible pinhole. The position of *both* electrodes must be adjusted with great nicety in order to get rays of sufficient hardness at the required pressure. The axis of the secondary discharge tube was set exactly parallel to the plane of the cathode. The secondary discharge was maintained by a small motor-driven Wimshurst, the anode being earthed. At first the discharge was intermittent, and the rays far from homogeneous, a difficulty appearing insuperable until it was accidentally found, by touching the bulb with the finger, that an earthed conductor F allowed to "brush" off on to the bulb rendered the discharge quite continuous if its distance was adjusted to suit the atmospheric conditions. When the apparatus was working well the image of the pinhole appeared on the screen over 40 cm. away as a sharp and almost perfectly steady circular spot, which could be read after a little practice to about 0·1 mm. The range of pressure over which suitable cathode rays were produced was exceedingly limited, and corresponded to a dark space in the main tube of about 3 cm., *whatever the nature of the gas*. By altering any of the dimensions of the secondary discharge tube another range could be obtained, but the above was used as being most satisfactory.

The pressure was not actually measured, but could be deduced from the length of the dark space; it ranged from about $\frac{1}{10}$ mm. in hydrogen to $\frac{1}{40}$ mm. in the other gases.

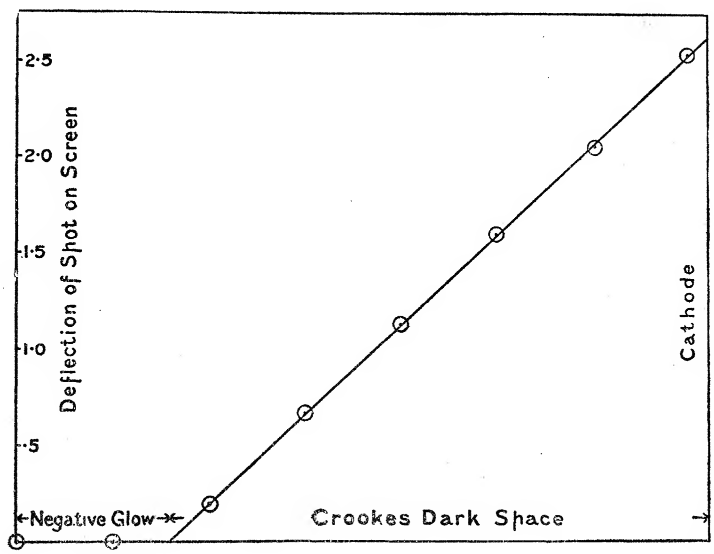
The potential between A and B was read on a Weston voltmeter, and by means of a double switch the same instrument was used for the determination of the standard field between B and C.

Experimental Procedure.

The apparatus was well washed with the gas to be used, and the pressure adjusted by an oil pump and a "charcoal liquid air" tube until the dark space was of suitable length and showed no tendency to alter, and the secondary discharge was also steady. The system of electrodes was then wound up until the pencil of cathode rays passed between B and C. When these two were both connected to earth a zero was obtained. A known potential was then put on between B and C, when a deflection of the spot was observed and measured on a scale attached to the screen. The plates were now lowered until the pencil passed through the dark space and the deflections taken corresponding to different distances from the cathode until the negative glow was reached. The plates were now raised and the observations checked on the return journey.

Results.

A typical set of readings obtained in this way is shown in the accompanying curve, in which deflections of the spot are plotted for different



positions in the dark space and negative glow. In the latter the deflection was always found to be zero, hence the electric force here is negligibly small compared with that in the dark space, a result agreeing with that found by the author in a previous paper (*loc. cit.*), "that the position of the anode, so long as it is in the glow, has no appreciable effect on the discharge." Measurable deflections commence *exactly* at the boundary of the dark space,

and within that region the deflection is proportional to the distance from the negative glow, the points lying practically on a straight line as indicated. (A critical examination of many sets of results shows a slight tendency for the curve to be a little steeper towards the ends than in the middle.)

This remarkably simple empirical result was obtained with hydrogen, air, oxygen, and argon, so that for these, and probably for all, gases under the conditions of these experiments *the electric force inside the dark space is in linear proportion to the distance from the edge of the negative glow.*

Since the total fall of potential across the dark space will be given by integrating the electric forces, it is clear that if we convert the deflections into electric forces this fall of potential will be the area of the curve bounded by the cathode and the edge of the negative glow, *i.e.* half electric force at surface of cathode multiplied by length of dark space. Before being able to obtain accurate measurements of this potential it will be necessary to find the correction for the curvature of the path of the exploring cathode beam.

Assuming the distribution found above, let $\mu =$ electric force at unit distance from the negative glow, then, if the length of the dark space is D, the equation of motion of an electron at distance y from the cathode is

$$\left(\frac{md^2y}{dt^2} = e\mu\,(\mathrm{D}-y)\right).$$

If l is the diameter of the tube, and v the velocity of the particles in the cathode stream, entering at a point y' from the cathode and leaving at y, solving the above equation, we get

$$\mathrm{D}-y = (\mathrm{D}-y')\cos\frac{l}{v}\sqrt{\frac{\mu e}{m}},$$

whence
$$y-y' = (\mathrm{D}-y')\left(1-\cos\frac{l}{v}\sqrt{\frac{\mu e}{m}}\right).$$

This is the actual displacement in the tube; to obtain the total deflection at the screen at distance p from the tube, we must add p times the value of dy/dx at the point of emergence, which is

$$\frac{p\,dy}{dt} = \frac{p}{v}(\mathrm{D}-y')\sqrt{\frac{\mu e}{m}}\sin\frac{l}{v}\sqrt{\frac{\mu e}{m}}.$$

Putting in the approximate values of sine and cosine, and adding, we obtain the total deflection

$$\frac{\mu\,(\mathrm{D}-y')\,le\,(\frac{1}{2}l+p)}{mv^2}\left[1-\frac{\mu e}{mv^2}\,\frac{l^2\,(\frac{1}{24}l+\frac{1}{6}p)}{\frac{1}{2}l+p}\right],$$

the part in square brackets being the correcting factor required.

Under a uniform field X, the total deflection is, in the same way,

$$\frac{\mathrm{X}e}{mv^2}l\left(\tfrac{1}{2}l+p\right).$$

Let K be the actual deflection when $y'=0$, *i.e.* for a ray grazing the cathode, and E the uniform electric force necessary to give unit deflection, then, putting in the numerical values of p and l actually used in the experiment,

$$\mathrm{K}=\frac{\mu\mathrm{D}}{\mathrm{E}}\left(1-0{\cdot}053\frac{\mu}{\mathrm{E}}\right).$$

But the total fall of potential is

$$\begin{aligned}\tfrac{1}{2}\mu\mathrm{D}^2 &= \tfrac{1}{2}\frac{\mathrm{KED}}{(1-0{\cdot}053\,\mu/\mathrm{E})}\\ &= \tfrac{1}{2}\frac{\mathrm{KED}}{(1-0{\cdot}053\mathrm{K}/\mathrm{D})},\ \text{putting in approximate value of } \mu/\mathrm{E},\\ &= \tfrac{1}{2}\mathrm{E}(\mathrm{KD}+0{\cdot}053\mathrm{K}^2).\end{aligned}$$

The value of K is obtained by plotting the deflections as described above, and finding where the straight line drawn through them cuts the cathode.

Distance from cathode in cm.	Hydrogen.				Air.	Oxygen.			Argon.
0·1	10·6	16·8	22·0	25·3	25·0	19·9	21·5	28·7	26·5
0·6	8·8	13·3	18·2	20·5	20·4		17·5	22·8	21·0
1·1	7·1	10·5	14·4	16·0	15·5	12·5	13·9	17·5	17·0
1·6	5·6	8·0	11·0	11·5	11·0		10·3	12·0	12·5
2·1	4·0	5·4	7·8	6·6	7·2	6·0	7·0	6·9	8·2
2·6	2·5	3·2	3·6	1·9	2·6	3·0	3·5	0	4·0
3·1	0·2	0	0	0	0	0	0		0
3·6	0								
Length of dark space …………	3·20	3·10	3·10	2·81	2·86	3·05	3·10	2·70	3·02
Volts per cm. per cm. deflection	144	135	146	152	156	137	139	140	148
Total potential calculated in dark space	270	369	536	595	590	442	493	602	610
Potential between electrodes …	265	375	530	610	583	445	495	610	620

In the accompanying table are given the deflections observed, the fall of potential in the dark space calculated by the above formula, and the voltage actually observed between the electrodes. It will be seen that, although the voltage (and with it the current in the tube) was varied over a wide range,

the calculated fall of potential, though more often less than greater, never differs from the observed by more than experimental error. From this the author arrives at the conclusion that, under the conditions of the experiment, practically the whole of the potential fall takes place in the Crookes dark space, and is distributed within it in the form of a continuous parabolic field.

The so-called "Kathodensprung."

It will be seen that, considering the close agreement of the fall of potential in the dark space with that between the electrodes, it is difficult to find room for the fall of the order of 20 volts close to the surface of the anode observed by Skinner, and quite impossible to do so for one of 80 volts at the surface of the cathode recently measured with an exploring wire by Westphal (*loc. cit.*). One is therefore driven to the conclusion that the sound does not take up the correct potential when used near the cathode. A careful consideration of the conditions under which the experiments were performed suggests the following possible explanation.

There is little doubt that at the surface of the cathode, when steady discharge is taking place, streams of positive ions—"Canalstrahlen," represented in the figure by heavy lines—are falling upon the surface of the cathode, and by their impact liberating streams of negative ions—cathode rays, represented in the figure by light lines travelling in the opposite direction. Let P be a small material obstacle introduced into such a system, and let it for an instant be at the same potential as the cathode. Such an obstacle, if sufficiently small compared with the length of the dark space, will interfere inappreciably with the supply of + ions, the bulk of which are almost certainly generated near or in the negative glow, but it will absolutely prevent the bombardment of that part (*a b*, fig. 2) of the cathode immediately beneath it, which part will at once cease to liberate − ions.

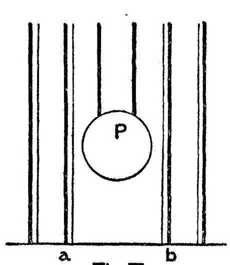


Fig II

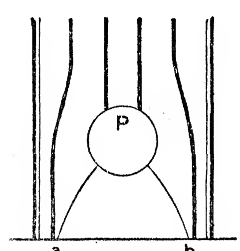


Fig III

P is now being bombarbed with ions of only one sign, and its potential must inevitably rise. As this happens it will deflect the + ions passing

close to it out of their normal path, making the "shadow" or inactive part $a\,b$ still larger (fig. 3), until finally its potential will rise so high that it is able to deflect to itself the $-$ ions generated at the boundaries of $a\,b$ in sufficient numbers to exactly balance the supply of $+$ ions in whose direct path it still lies, when equilibrium potential will be established.

Since the equilibrium potential between the obstacle and the cathode is only concerned with the *relative* intensity of the supplies of $+$ and $-$ ions, it will be practically independent of the gas pressure and the current density, and, in fact, might be expected to behave very much as does Westphal's "Kathodensprung," which seems in all probability non-existent in a normal unobstructed discharge.

Theoretical Aspects of the Results.

A detailed enquiry into the theoretical considerations involved in the somewhat remarkable result of this investigation is beyond the scope of the present paper, but a few of the more salient points may be referred to with advantage.

Since the rate of change of electric force in the dark space is uniform, the latter must be a region in which the free electrification has a uniform excess positive density ρ, such that if V is the potential fall across the dark space and D its length, $\rho = V/D^2$.

The author has shown (*loc. cit.*) that if V is constant D varies very nearly universely as the pressure; hence for a constant voltage ρ varies directly as the square of the pressure. It, however, bears no simple relation to the voltage or the current density at constant pressure.

The assumption made for simplicity by the author in the above paper that the density of the free negative electrification in the dark space might be neglected is clearly incorrect, since the excess of positive ions must carry more current in the stronger parts of the field than they do in the weaker ones, so that in the latter ions of both signs must be present to maintain the flow. It appears, indeed, that the actual number of ions of both signs per cubic centimetre increases as we move away from the cathode, their algebraic sum being the constant ρ, which becomes zero with surprising suddenness at the edge of the negative glow.

If we suppose that at the surface of the cathode a constant fraction of the total current is carried by this excess of positive ions, and that their velocity is proportional to the field at that point, we obtain a value of the mobility $k_1 \propto c\mathrm{PD}^3\mathrm{V}^{-2}$, which is the same expression (with different constants) as that obtained on other premises in the above paper, and shown to be notably constant for a given gas.

The fall of potential across the new dark space discovered by the author in helium and hydrogen,* must, from the results of this investigation, be taken as $2\mathrm{V}d/\mathrm{D}$ instead of $\frac{3}{2}\mathrm{V}d/\mathrm{D}$, which works out at 20 volts for hydrogen, 40 volts for helium, but the considerations involved in the theory suggested for this phenomenon are not affected.

Summary of Results.

(1) The electric force in the negative glow is negligibly small compared with that in the dark space.

(2) The electric force in the dark space is very nearly in linear relation to the distance from the negative glow; and, hence,

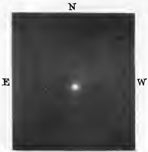
(3) The dark space is a region of uniform positive electrification ceasing with great suddenness in the negative glow.

(4) The total fall of potential inside the dark space, calculated from the results obtained, agrees within the error of experiment with that observed across the electrodes.

(5) The method of exploring points is inapplicable to the dark space, and the large falls of potential at the surface of the cathode, observed by its use, are probably non-existent in an unobstructed discharge.

In conclusion, the author wishes to express his indebtedness to Prof. Sir J. J. Thomson, both for the method employed and for his kind help and encouragement during the investigation.

* F. W. Aston, 'Roy. Soc. Proc.,' 1907, A, vol. 80.



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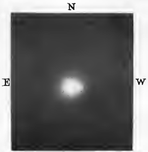

Fig. 2.

1910, May, 26 d. 9 h. 40 m. to 10 h. 10 m.

(Photographs of the Nucleus of Halley's Comet.)

FIG. 3.—Visual Observations of Spectrum, May 22, 23, 26.

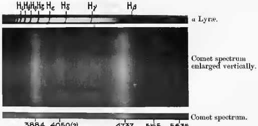

FIG. 4.—Photograph of Comet Spectrum, with α Lyræ comparison.
(Quartz-calcite Spectrograph, 2-inch aperture, 18-inch focus.)